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ESTABLISHMENT OF RAPID X-RAY DIFFRACTION INSPECTION TECHNIQUES --ETC(U)
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TECHNICAL REPORT

NO. 12173

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ESTABLISHMENT OF RAPID X-RAY DIFFRACTION INSPECTION TECHNIQUES FOR RESIDUAL STRESSES

APRIL 1977

by SALVATORE B. CATALANO

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U.S. ARMY TANK-AUTOMOTIVE
RESEARCH AND DEVELOPMENT COMMAND
Warren, Michigan 48090

TECHNICAL REPORT NUMBER 12173

ESTABLISHMENT OF RAPID X-RAY DIFFRACTION INSPECTION TECHNIQUES FOR RESIDUAL STRESSES

BY

S. B. CATALANO

JUNE 1976

AMCMS CODE: 5397.OM.6350

Armor, Material Application and Technical Function

FOREWORD

This work was funded under the Materials Testing Technology Program DA project/task no. 5397.OM.6350, as authorized by the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts.

Appreciation is extended to AMMRC for the opportunity of working on this challenging project. Acknowledgements are extended to Dr. E. Petrick, Dr. J. Parks and Dr. D. Bowman for their direction at the outset of the program. Messrs. G. Conkol, R. Hakala, D. Sprague and W. Evans are especially to be thanked for their persistence in obtaining data used in this report.

ABSTRACT

An automatic stress analyzer has been used by the U.S. Army Tank-Automotive Research and Development Command (TARADCOM), for rapid measurement of residual stresses in track pins and torsion tubes. With this equipment measurements can be made from ten to one-hundred times faster than with conventional equipment. The equipment is a recent development and few are in existance. A unique feature of the unit at TARADCOM is that it has been interfaced with a computer for purposes of drawing isostress plots.

Work on used track pins showed no detrimental residual stress levels on the surface of the track pins. Measurements taken on sectioned surfaces of track pins revealed areas of tensile residual stress surrounded by compressive residual stresses, with steep stress gradients in between. These areas are in the region between the core and the induction hardened layer; cracking was observed here in laboratory tested track pins.

Vast differences are exhibited in both the isostress plots and the standard deviation of the measurements taken on torsion tubes where failure initiation occurred on the bodies of the tubes as opposed to instances where failure initiation did not occur in the body of the tube or where failure did not occur at all. These differences may be due to differences in the uniformity of the shot peening operation. Regions of lower compressive residual stress and associated steep stress gradients may act as stress risers and cause premature failure.

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INTRODUCTION AND BACKGROUND

Residual stresses are induced in components during heat treatment, machining, welding, casting and metal-working processes. These stresses can be of an undesirable nature, concentration, or level due to faulty processing or improper component design, adversely affecting functional performance and durability. Cumulative high dynamic and residual stresses in service may exceed design load limits of the parts. X-ray diffraction is capable of measuring residual stresses nondestructively. Until recently, the method was time-consuming, required expert personnel to operate the equipment and was limited to small parts or cut sections.

Residual stresses in metals are now easily and quickly measured with recently developed automated x-ray diffraction equipment. Measurements with automated equipment can be made in as short a time as a half minute, whereas previously measurements took as long as 45 minutes per reading.

The x-ray beam size is usually 1/8 inch in diameter or smaller, consequently, it is usually necessary to take readings at many spots rather than just one spot. Often it is desirable to take readings at 100 spots or more. Consequently, time savings using automated equipment can be considerable. These large time savings will enhance interest in residual stresses and it has caused us at TARADCOM to begin taking a closer look at the effects residual stresses have on serviceability of tank-automotive components. Eventually, we could expect to include residual stress levels as engineering requirements.

In general, the Tank-Automotive Research and Development Command's interest in rapid residual stress measurement was prompted by such prospects as:

1. Increased vehicular reliability through in-line go-no-go quality gaging of residual stresses in high stress tank-automotive components.

2. Improved vehicular component design.

3. Lighter weight component design.

4. Improved armor protection.

5. Improved field failure analysis.

6. The ideas generated for new programs utilizing rapid residual stress measuring equipment.

APPROACH AND EQUIPMENT

The method used in this work is the x-ray diffraction method as described in the SAE Technical Report No. 182.

In the past, a conventional x-ray diffractometer was used for residual stress analysis work. Figure 1 shows the General Electric Model XRD-3 used in the past for this purpose. It consists of an x-ray tube, a goniometer, an x-ray detector, and an electronic counter and timer. With this type of equipment three x-ray intensity measurements are made for two different settings of x-ray incidence angle. From the data obtained the value of residual stress is calculated. The procedure takes about 45 minutes per measurement.

The equipment used in this project was an automatic stress analyzer manufactured by the American Analytical Corporation. This equipment is shown in Figure 2. It is x-ray diffraction equipment automated to measure residual stress using the method described in the SAE Technical Report No. 182. The automated equipment makes use of two x-ray tubes, two goniometers, four x-ray detectors used in pairs (each pair being coupled with a peak-seeking servomechanism), four x-ray activity meters, and electronic circuitry to calculate and display values of residual stress on a strip chart recorder. The strip chart recorder pen oscillates in response to oscillations of the peak-seeking servomechanisms. After about a minute the pen has drawn enough oscillations for an estimate of the center of oscillation to be determined and the residual stress to be read directly from the strip chart recorder. The accuracy of the automatic stress analyzer is $\pm$ 5,000 psi as compared to $\pm$ 3,000 psi for the conventional x-ray diffractometer. However, the stress analyzer is anywhere from 10 to 100 times faster than the conventional x-ray diffractometer method. Because of its greater accuracy, the conventional x-ray diffractometer is used as a check for calibration of the automatic stress analyzer.

On samples, such as weldments, where the residual stress fluctuates rapidly, it is necessary to use a small size x-ray beam. The beam size is controlled by the size of collimator used; the automatic stress analyzer is equipped with three sizes: .030 inch, .045 inch and .060 inch. Either the 30 mil or the 45 mil collimator would be used on weldments. In the research work preliminary to this study it was found desirable to plot isostress lines from the matrix of residual stress readings taken on weld samples. Figure 3 shows a hand-drawn isostress plot of residual stresses in the heat-affected zone of a weldment. The heavy solid line represents the zero level of stress. The broken lines represent the tensile regions and the light weight solid lines represent compressive regions. With such an isostress plot one can at a glance locate maximums and minimums of residual stress, the location of the zero level of residual stress, areas in compressive stress, areas in tensile stress and areas containing steep stress gradients. Since isostress plots are time consuming to draw by hand and are therefore an obvious bottleneck in an otherwise rapid scheme for performing residual stress analysis, an automated process of drawing isostress lines was developed. The equipment used to automate this process includes:

1. Analog to digital converter to convert the analog data received from the automatic stress analyzer to digital output.

2. Paper tape punch on a teletype with which digital data are punched onto paper tape.

3. Hewlett-Packard 9830 Desk Top Computer (equipped with an **x - y** plotter) which accepts digital data from paper tape.

4. Computer program for processing the data for x-y plotter use in drawing isostress lines. A listing of the computer program is given in the Appendix.

Figure 4 shows the computer-drawn isostress plot of the same data that was used for the hand-drawn isostress plot shown in Figure 3.

Most of the work on this project deals with torsion tubes and used track pins submitted for possible reclamation processing. A few measurements have also been made on such varied components as gears, road wheels, **pitman** arms and ESR **steel.** The approach taken in the work with track pins and torsion tubes had several steps:

1. Mark spots on the component part where residual stress measurements were to be taken.

2. Record residual stress measurements at the marked spots.

3. Look for significant trends in measured residual stress levels that might be responsible for future failure initiation.

4. Mechanically exercise the part in fatigue test machine. The fatigue test machine is shown in Figure 5.

5. Repeat steps 1 thru 4 until failure occurs or until the end of the planned test period.

RESULTS

Work on used track pins showed no detrimental residual stress levels on the surface of the pin either before or after fatigue testing. Never-the-less, track pin failures occurred at random during fatigue testing. Consequently, surface residual stress could not be used as an indicator of potential for early pin failure or as an indicator of eminent pin failure. Measurements were then taken on sectioned surfaces of track pins. Residual stress scans on sectioned samples of induction hardened T-142 track pins revealed tensile residual stresses as well as steep stress gradients in the area of demarcation between the induction hardened layer and the inner core as shown in Figure 6 and 7. Stress gradients and tensile stresses are known to be important factors in causing fracture. Cracking has been observed along this area of demarcation on track pins fractured under fatigue testing in the Laboratory.

One puzzling aspect of the measurements taken on the surface of track pins is that the level of compressive residual stress on the portion of the pin that is both induction-hardened and shot-peened is no greater than on the portion that is only induction hardened. This fact implies either that nothing is gained by the shot peening operation or that the benefits of shot peening (i.e., inducing compressive residual stress on the surface) have been worn away by friction during usage. The latter is probably not the case since preliminary residual stress data on new track pins also indicate that the shot-peened surface has no greater compressive residual stress than the induction-hardened surface before shot peening. This then stimulates some questions. For example:

1. Of what value has the shot peening operation been?

2. If the shot peening operation were eliminated, would a cost savings be realized without sacrificing track pin lifetime?

3. Alternatively, would track pin lifetime be increased if higher intensity shot peening were employed thereby imparting a greater compressive residual stress than that obtained from induction hardening?

Work has been proposed (internal to TARADCOM) to attempt to answer the above questions as well as to attempt to reduce the steep stress gradients observed in sectioned track pins thereby increasing track pin lifetime.

Work with torsion tubes revealed varying degrees of non-uniform surface residual stresses. This possibly implicates non-uniform shot peening. Areas on the surface of the torsion tube that may have been shot-peened less intensely than the remainder of the tube may exhibit lower compressive residual stress than the remainder of the tube. These areas may act as sites for potential failure initiation.

Grid lines were drawn on each torsion tube tested and residual stress measurements were taken at the intersections of the grid lines. Grid lines were drawn over the the entire length of two new and intact torsion tubes (for a total of 888 grid intersections on each tube). Grid lines were also drawn over a section of two broken torsion tubes in the vicinity of the break. One of these broken torsion tubes had over 400 grid intersections drawn on it; the other had almost 200. Figure 8 represents the grid lines drawn on the latter broken tube. The vertical lines were drawn on the tube at 24^{o} intervals around the tube. The jagged line represents the jagged edge where the tube broke. Residual stress readings taken at the intersections of the grid lines are shown by the numbers in this figure (represented in thousands of pounds per square inch). Negative signs indicate compressive stresses and positive signs indicate tensile stresses.

The data from these torsion tubes was processed and illustrated in three different ways:

1. Computer-drawn isostress plots were made for each of the torsion tubes tested.

2. Histograms were plotted for the data from each torsion tube.

3. Statistical quantities such as mean, standard deviation, skewness and kurtosis were calculated for the data from each torsion tube.

Inspection of the data from each tube shows fluctuations of stress from point to point. In particular, it shows isolated areas of lower compressive residual stress such as shown by the point circled in Figure 8. The degree of non-uniformity of surface residual stress for each torsion tube can be illustrated and comparisons between them made with the use of isostress plots, histograms and standard deviation of the data from each tube. The isostress plots are shown in Figures 9, 10, 11 and 12 and are to be visualized/associated with torsion tubes as illustrated in Figure 17. For ease of comparison and interpretation, the plots were made full scale in each case and the isostress lines were drawn in incremental steps of 10×10^3 psi. Figure 11 has four parts (i.e., a, b, c, and d), each part representing the four different sections of the entire length of that tube for which an isostress plot was made. Similarly, Figure 12 has 5 parts. Figures 13, 14, 15 and 16 show the computer plotted histograms of the data from each torsion tube tested. The cell size in the histograms was chosen to be 10×10^3 psi to correspond to the increment size of 10×10^3 psi used on the isostress plots. Table I is a compilation of the computer-calculated statistics of the data from each tube.

Comparison of the data from the four torsion tubes tested is very striking when presented in terms of uniformity of surface residual stress vs. performance of the tube in fatigue testing. Two of the four tubes endured the complete fatigue test (75,000 cycles) without rupturing. The other two tubes ruptured in the body of the tube. The two tubes that endured the complete fatigue test without rupturing displayed the most uniform surface residual stresses as evidenced by:

1. The most uniform isostress plots (see Figure 17).

2. The narrowest histogram displays.

3. The smallest standard deviations.

The two tubes in which fracture initiation occurred in the body of the tube displayed:

1. The least uniform isostress plots (see Figure 17).

2. The broadest histogram displays.

3. The largest standard deviations.

It may be significant to note from Table I that the tube with the largest standard deviation failed first, the tube with the next largest standard deviation was the next to fail, etc. The data from Table I is plotted in Figure 18. Note that a line rather than a point was plotted on the graph for tube no. RKO-18 reflecting the fact that it was not carried out to failure. Both tubes (RKO-18 and WELDED) that endured the fatigue test limit of 75,000 cycles had standard deviations less than 8.0×10^3 psi. On the basis of this data, it was decided that preliminary quality assurance requirements call for the shot peening operation on torsion tubes to impart uniform residual stress levels; the uniformity shall be determined by the standard deviation of 200 residual stress measurements taken at random positions over the entire length of the tube. A standard deviation of 8×10^3 psi or less will be considered acceptable under this preliminary quality assurance requirement. This figure will be updated as needed after sufficient statistical quantities of data have been gathered.

DISCUSSION

Residual stress measurements can now be made in a small fraction of the time required in using a conventional diffractometer. This then permits the use of x-ray diffraction residual stress measurements to be economically used for in-line gaging of mechanical parts, for quality assurance purposes and for problem solving of field failures rather than being used exclusively for research work. The stress studies performed at TARADCOM on track pins and torsion tubes would not have been feasible without automated x-ray diffraction equipment.

There are only about a dozen or so automated x-ray diffraction units for residual stress measurements in the world. Most of them are in this country and were built in the United States. A Japanese company markets a version of this also. Of the dozen or so users of automated x-ray diffraction equipment for rapid residual stress measurement, it is likely that TARADCOM is unique in having interfaced their equipment with a computer for automatic plotting of isostress lines. This unique capability enables TARADCOM to use residual stress measurements as a tool for research and problem solving as well as for quality assurance. An example of research work that this equipment will allow us to perform rather easily is an investigation of residual stress patterns in weldments as a function of the individual weld parameters. This will enable determination of weld parameters required to achieve optimum weldments.

The work that we have done on track pins and torsion tubes are examples of problem solving work this equipment allows us to perform. The solution to the track pin breakage problem may be to change the manufacturing processing to eliminate or at least decrease the steep stress gradients shown in Figures 6 and 7. The solution to premature failures of torsion tubes may lie in the shot peening process. It is expected that improving the shot peening operation (so that it results in a more uniformly shot peened surface) may result in fewer premature failures of torsion tubes. A visual check is not sufficient to determine uniformity of shot peening; a residual stress scan is required.

Examples of quality assurance work that this equipment will allow are such things as in-line gaging of stress relieved parts, shot peened parts, heat treated parts, machined parts, castings and weld parts, etc. In this application the equipment would be set in the go-no-go mode of operation and an alarm would be tripped when the part did not meet the specified level of residual stress.

CONCLUSION

Interfacing automated x-ray diffraction equipment with the computer for drawing isostress plots has resulted in a rather unique tool. Never before have we or anyone else had the capability of measuring residual stresses and plotting the isostress lines so rapidly.

The work performed on this project with torsion tubes reveals that automated x-ray diffraction is a viable technique for inspection of torsion tubes for uniformity of the shot peening operation. If used for quality control purposes, a sampling plan would be required. In general this technique should prove fruitful for checking level of residual stress imparted by the shot-peening operation as well as for uniformity of shot peening. Sampling plans adopted would depend on part size and shape and degree of coverage desired in testing.

Work performed on track pins did not lend itself to quality control. It did, however, demonstrate the usefulness of automated x-ray diffraction in problem solving or for work of a research nature.

The equipment can be used in a research, problem solving or in-line gaging capacity. It has been very instrumental in pointing the way to solutions of problems for TARADCOM and perhaps can be used in research work, or in helping solve problems, or for quality assurance/in-line gaging for other Commands/Installations.

Automated x-ray diffraction is a non-destructive test and very possibly may prove to be a great asset to the field of materials technology in the near future.

RECOMMENDATIONS

This project dealt with a material testing technique (MTT). At times the work interfaced with work more appropriately considered to be R&D and at other times with work more appropriately considered to be manufacturing methods and technology (MM&T). The MTT work is completed. The recommendation is that the automated x-ray diffraction technique is a viable non-destructive technique which can be utilized for R&D, problem solving and quality assurance purposes. All three of these uses have been made of this technique in this work to some extent.

The need for further work has surfaced in the R&D and MM&T aspects. For example, there is a need to employ this technique for quality assurance of the shot peening process. A requirement could be added to shot-peening specifications calling for desired levels and uniformity of residual stresses imparted by shot-peening operations. In particular, for torsion tubes preliminary data (i.e. data from the four torsion tubes tested in this project) indicate a requirement for a standard deviation of 8×10^3 or less in the residual stress readings on the surface of the torsion tube. Before such a requirement is implemented a large number of readings should be taken on a large number of torsion tubes and each tube fatigue tested to failure. It is suggested that an MM&T project be funded in which 200 readings are taken on 100 torsion tubes and the standard deviation of the readings on each tube be plotted against cycles to failure of that tube. This will enable a more accurate choice of limit for the standard deviation of residual stresses on the surface of the tube. This then would be a means of measuring and controlling the uniformity of the manufacturing method (shot peening) of imparting compressive residual stress on the surface of the torsion tube.

On track pins the need for additional study has also surfaced. It was noticed that there was no greater residual stress imparted in the track pins by shot peening than that induced by the induction-hardening process which preceeded the shot peening process. Of what value then was the shot peening? Can a cost savings be realized by eliminating the shot peening step without degrading pin lifetime? Alternatively, can pin lifetime be increased by employing shot peening of great enough intensity to impart greater compressive residual stress than already imparted in the pin by the induction hardening step which preceeded the shot peening? Others at TARADCOM have reported that the shot-peening operation was beneficial, resulting in greater pin lifetime. However, the report did not include residual stress data; the results obtained would be expected only if the shot peening operation induced more compressive residual stress in the part than already induced by the induction hardening step. It is recommended then that additional tests be made of fatigue life vs. shot peening. The shot peening intensity should be varied from zero to a value which imparts considerably greater compressive residual stress than already present due to the induction hardening step.

The tensile residual stresses surrounded by steep stress gradients in track pin cross-sections as observed in this project suggests further R&D work. The objective of such research work would be to eliminate, diminish, redistribute, or change direction of tensile residual stresses and steep stress gradients in a manner that would be beneficial to track pin lifetime. This perhaps could be accomplished by altering process variables.

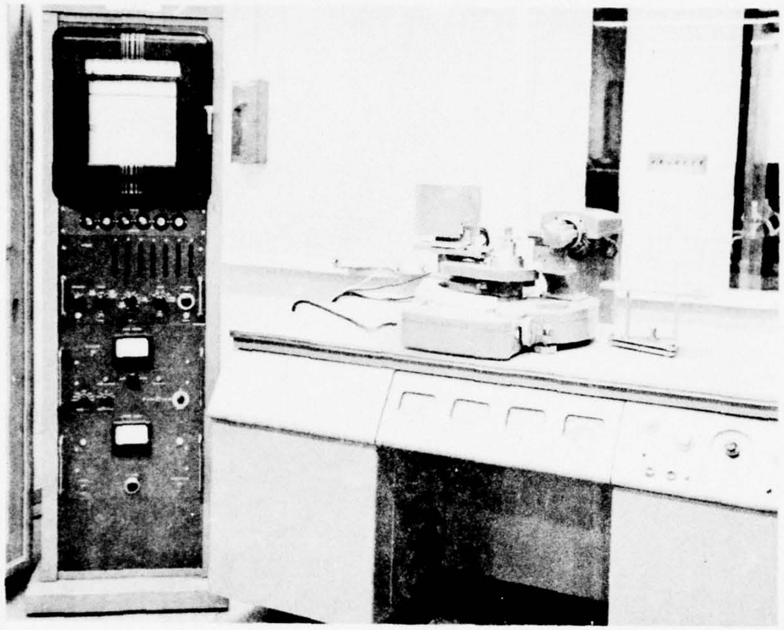


Figure 1 - General Electric X-Ray Diffraction Unit
Model XRD-3

Figure 2 - Automated X-Ray
Diffraction Unit
for Rapid Measurement of Residual
Stress

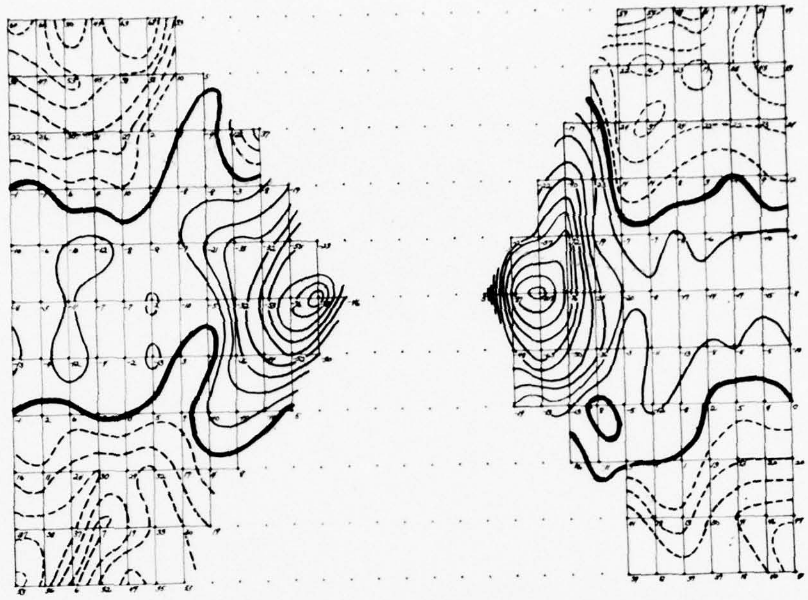


Figure 3 - Hand-Drawn Isostress Plot of Heat Affected Zone in Weldment

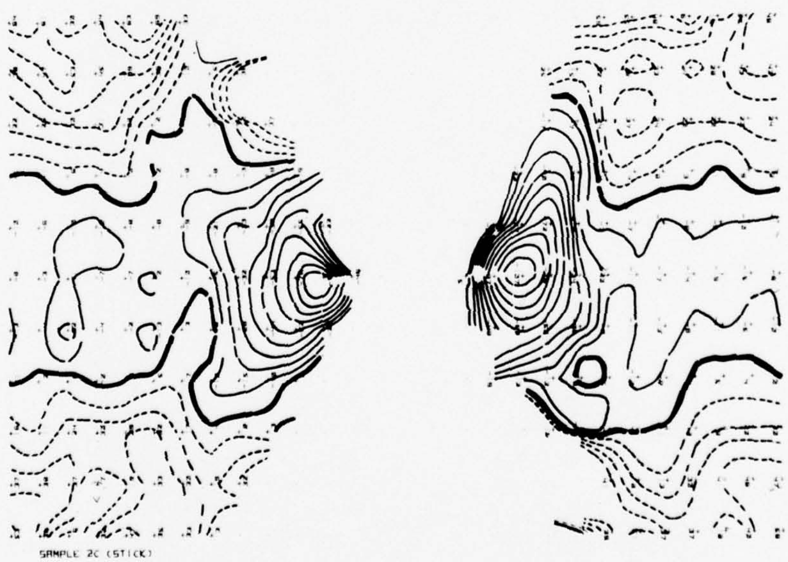


Figure 4 - Computer-Drawn Isostress Plot of Heat Affected Zone in Weldment

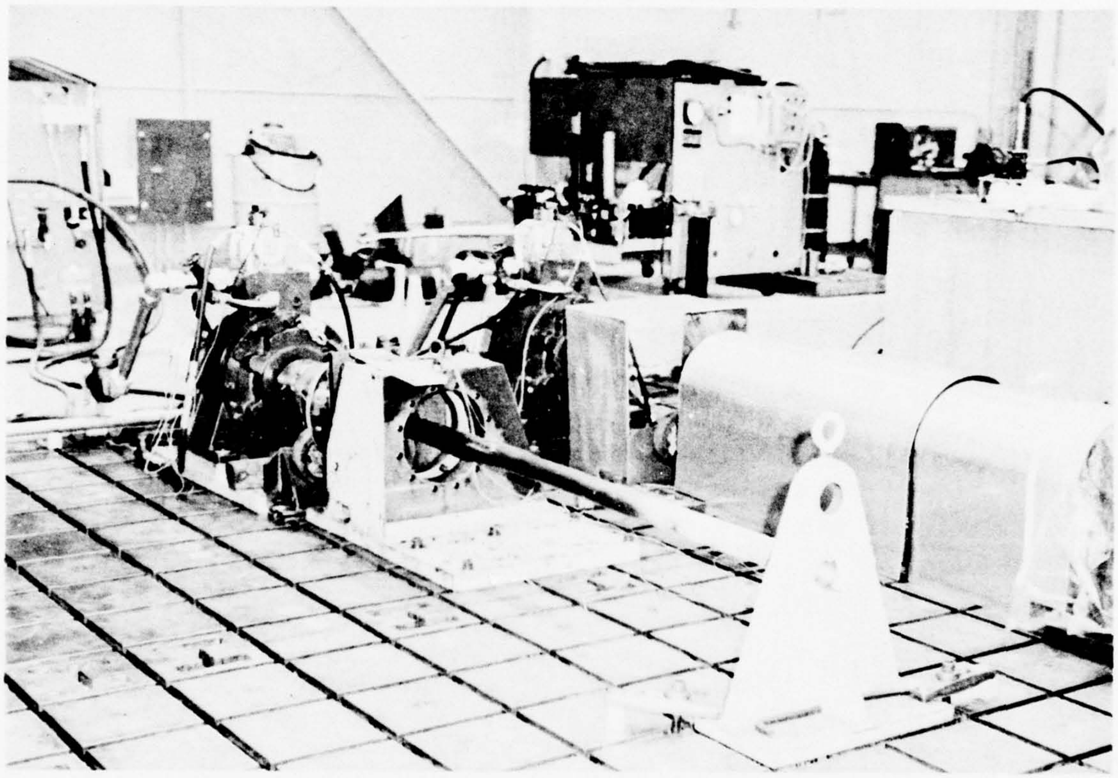


Figure 5 - Fatigue Test Machine with Torsion Tube in Place for Torsional Fatigue Test

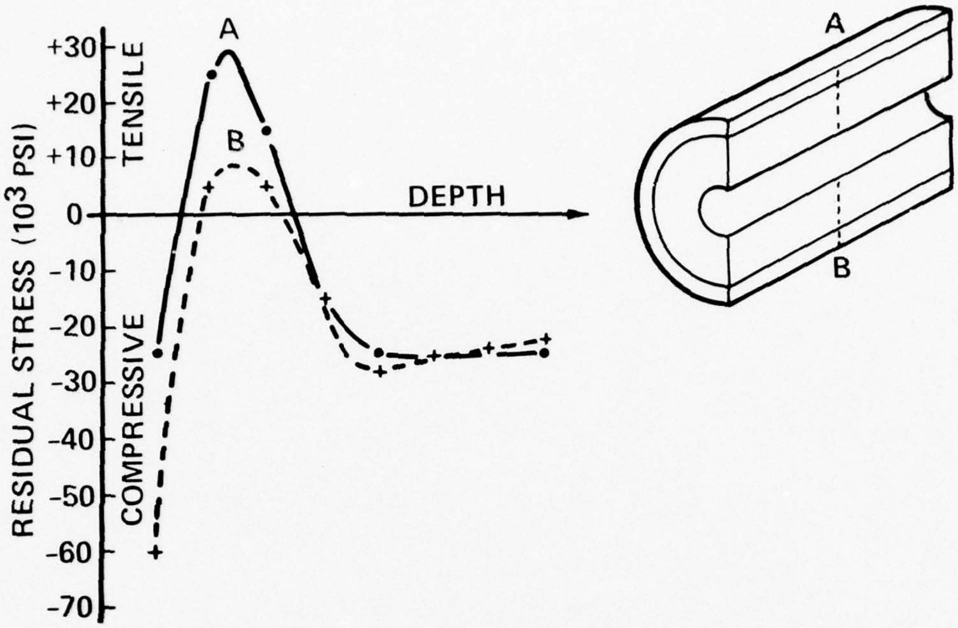


Figure 6 - Longitudinally-Directed Residual Stresses in Sectioned Track Pin

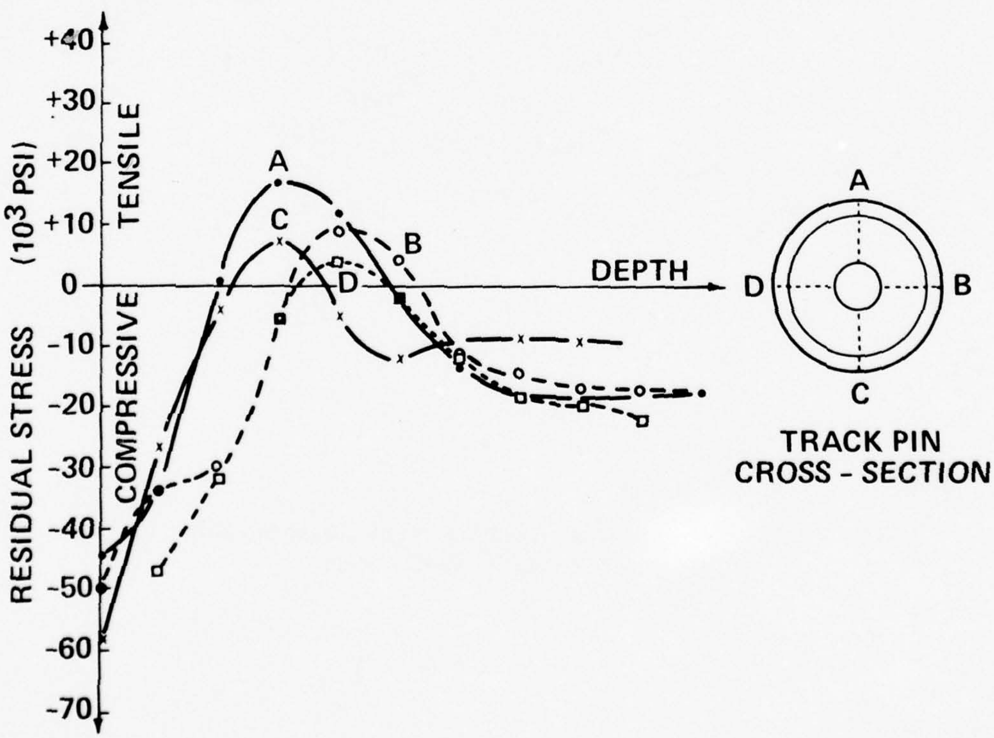


Figure 7 - Tangentially-Directed Residual Stresses in Sectioned Track Pin

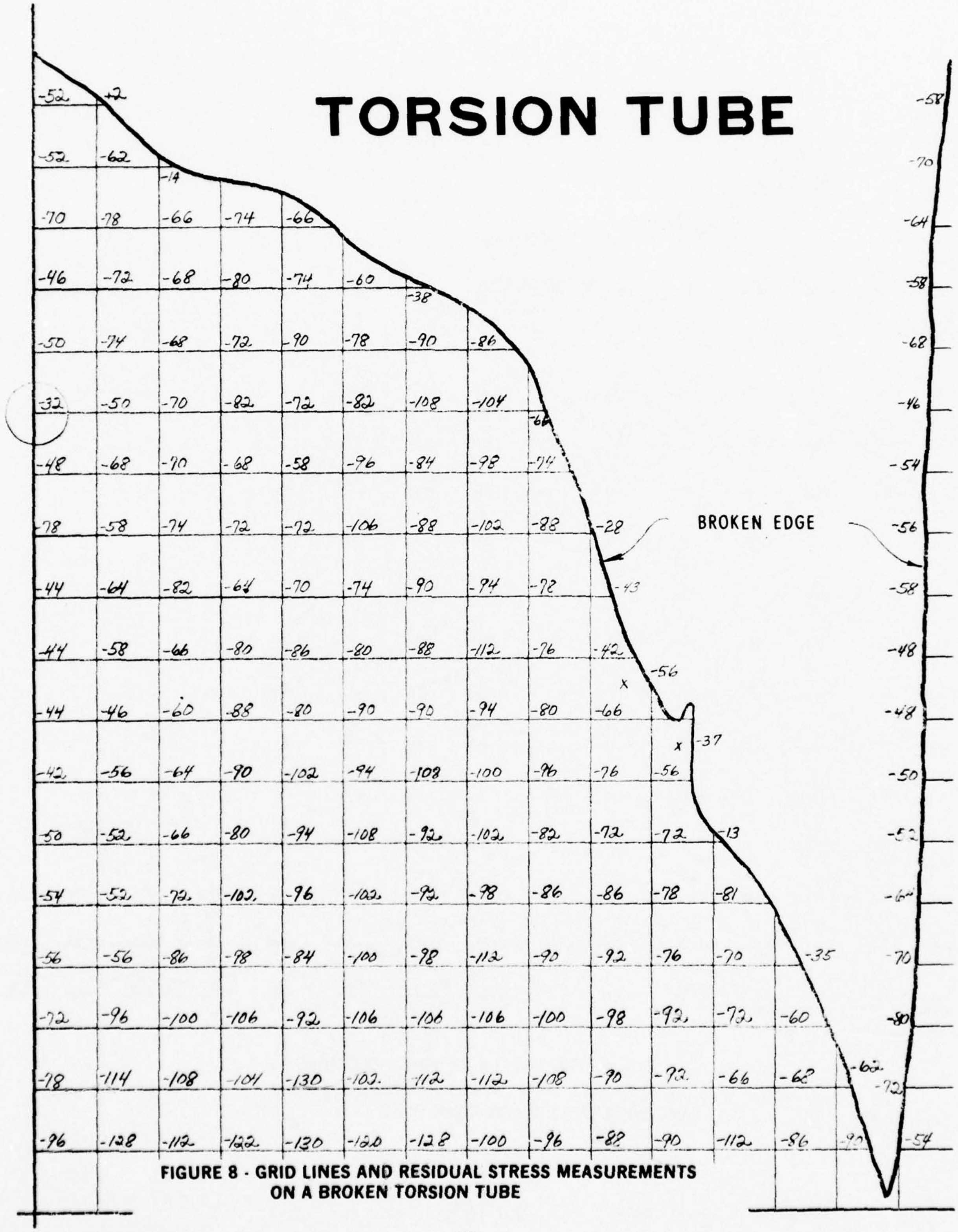


FIGURE 8 - GRID LINES AND RESIDUAL STRESS MEASUREMENTS ON A BROKEN TORSION TUBE

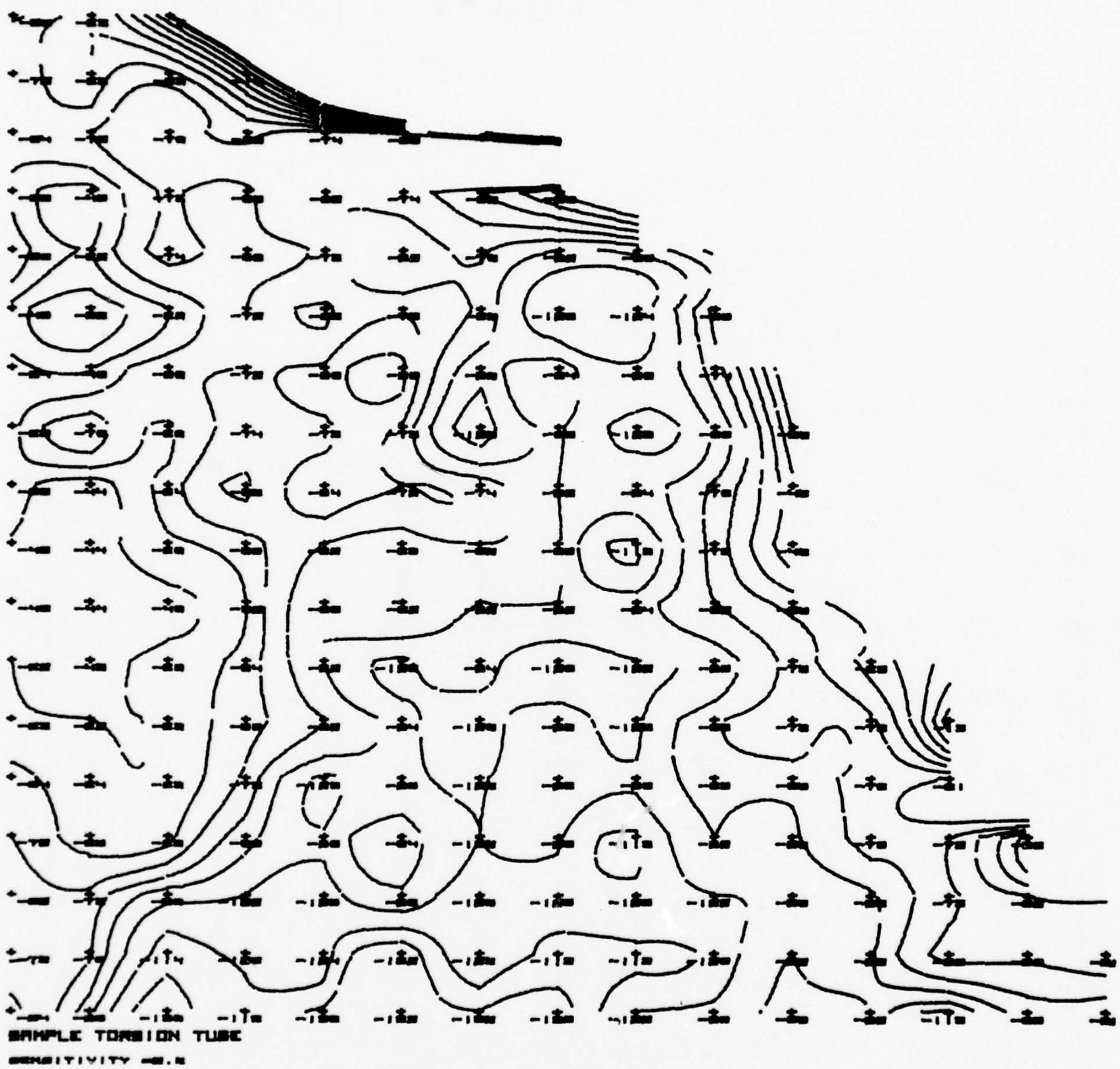
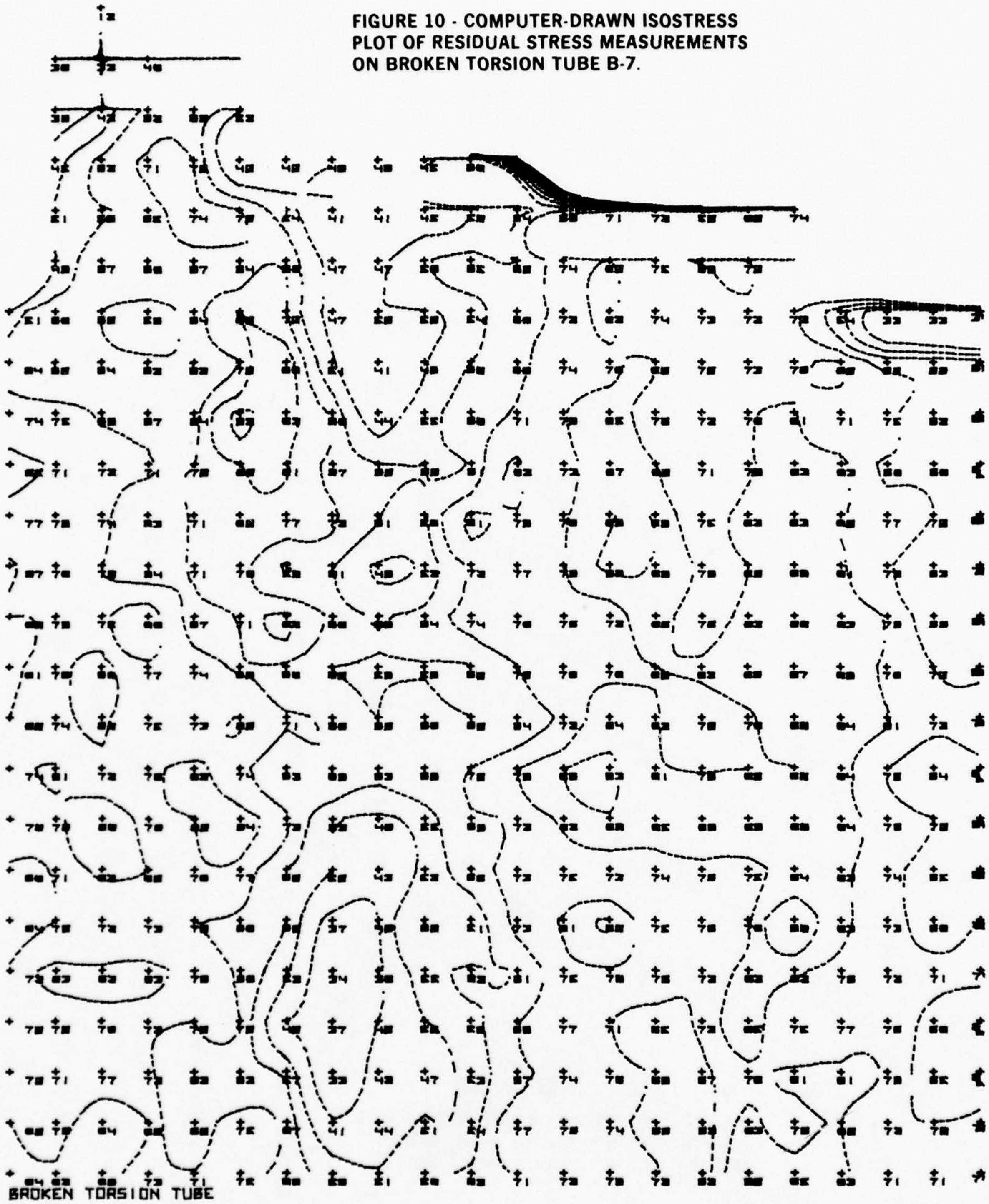


FIGURE 9 - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON BROKEN TORSION TUBE B-18.

FIGURE 10 - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON BROKEN TORSION TUBE B-7.



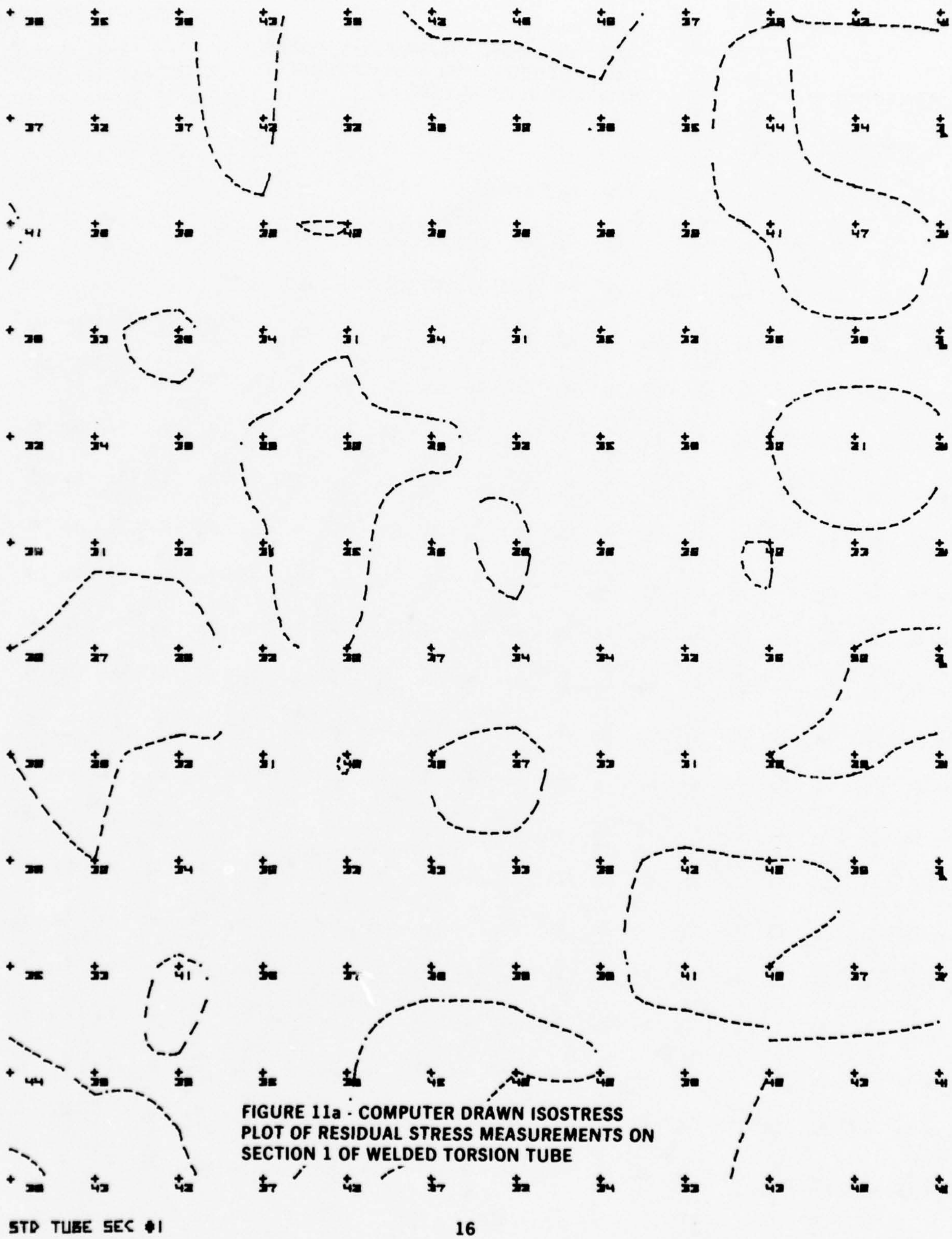


FIGURE 11a - COMPUTER DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 1 OF WELDED TORSION TUBE

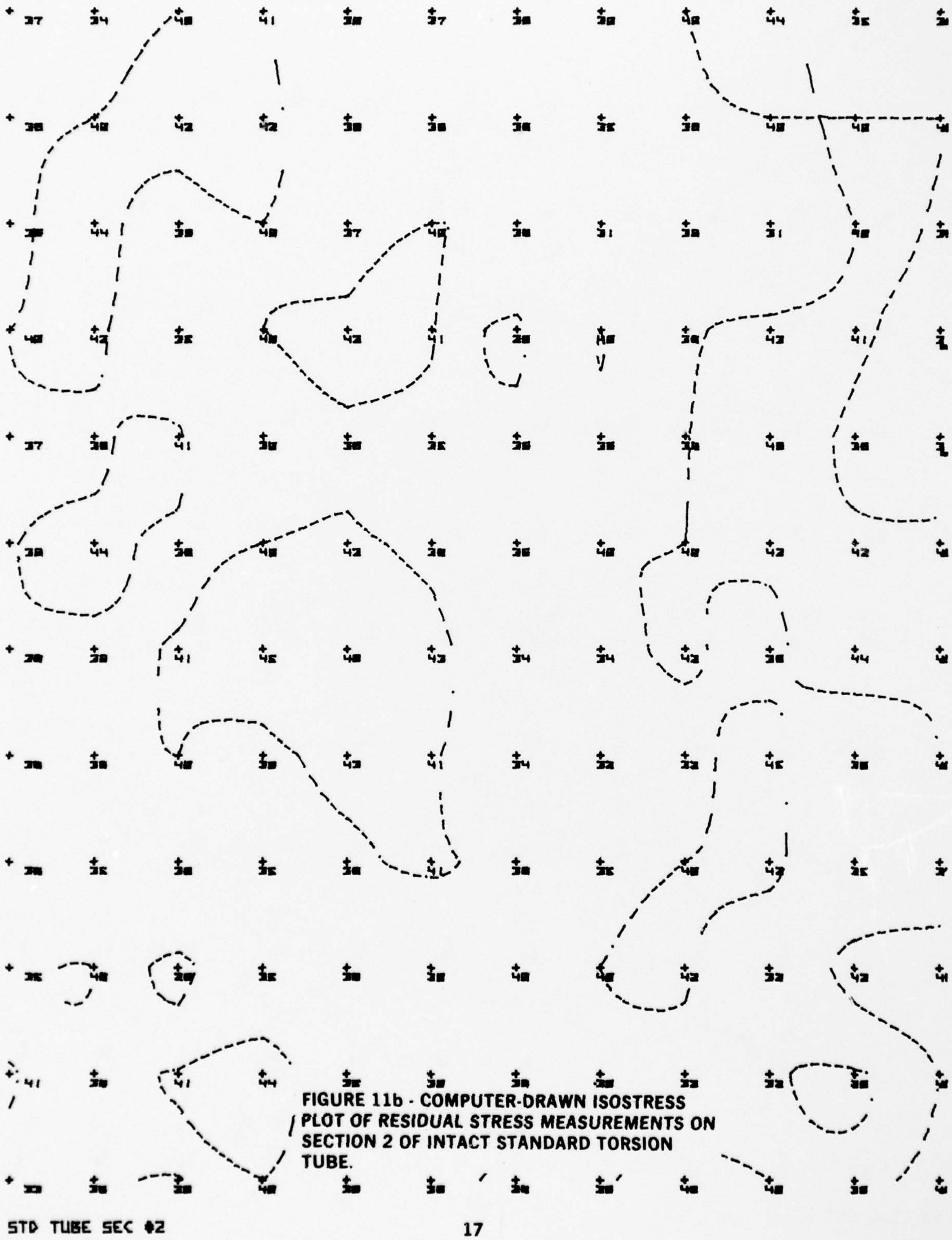


FIGURE 11b - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 2 OF INTACT STANDARD TORSION TUBE.

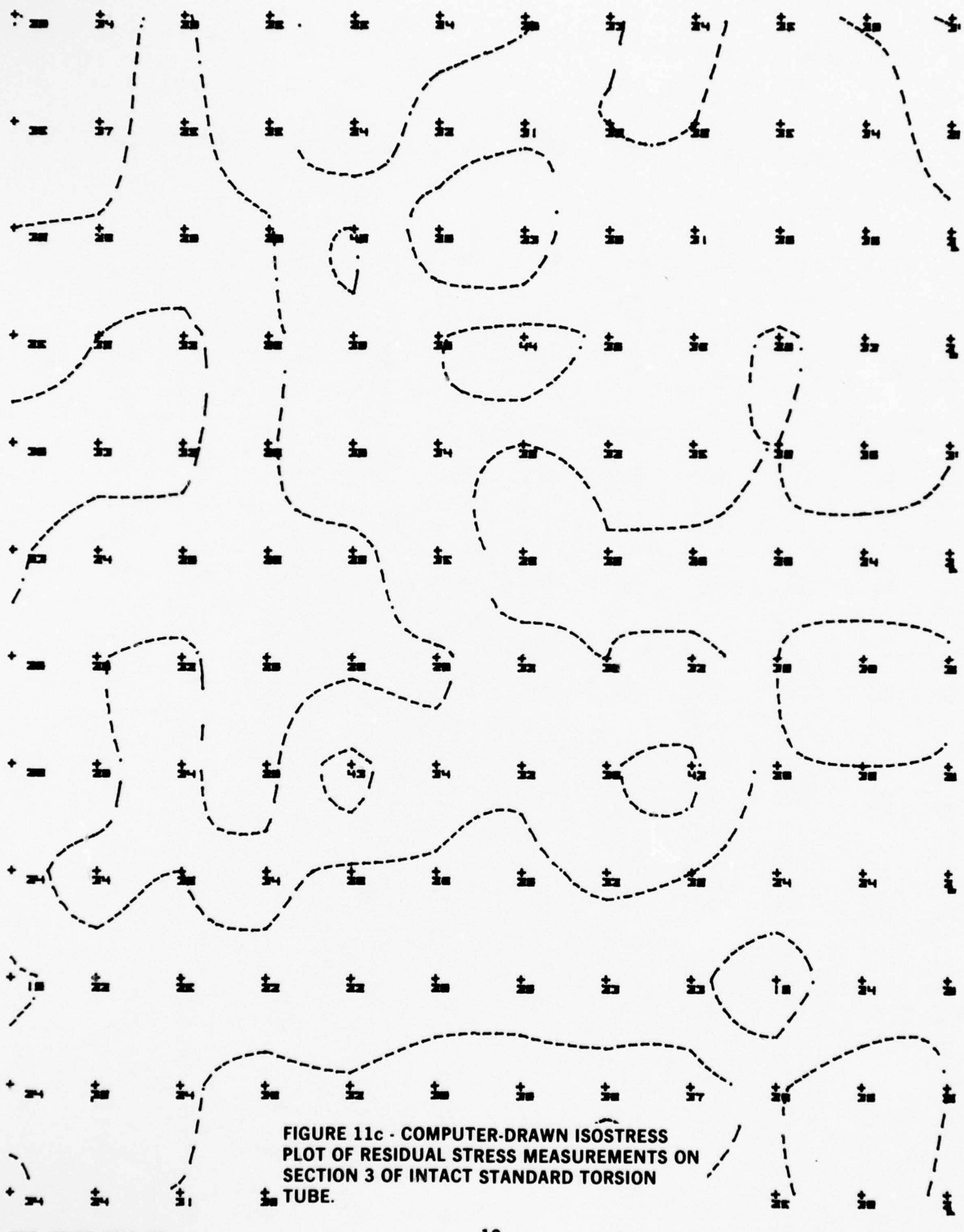


FIGURE 11c - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 3 OF INTACT STANDARD TORSION TUBE.

STD TUBE SEC #5

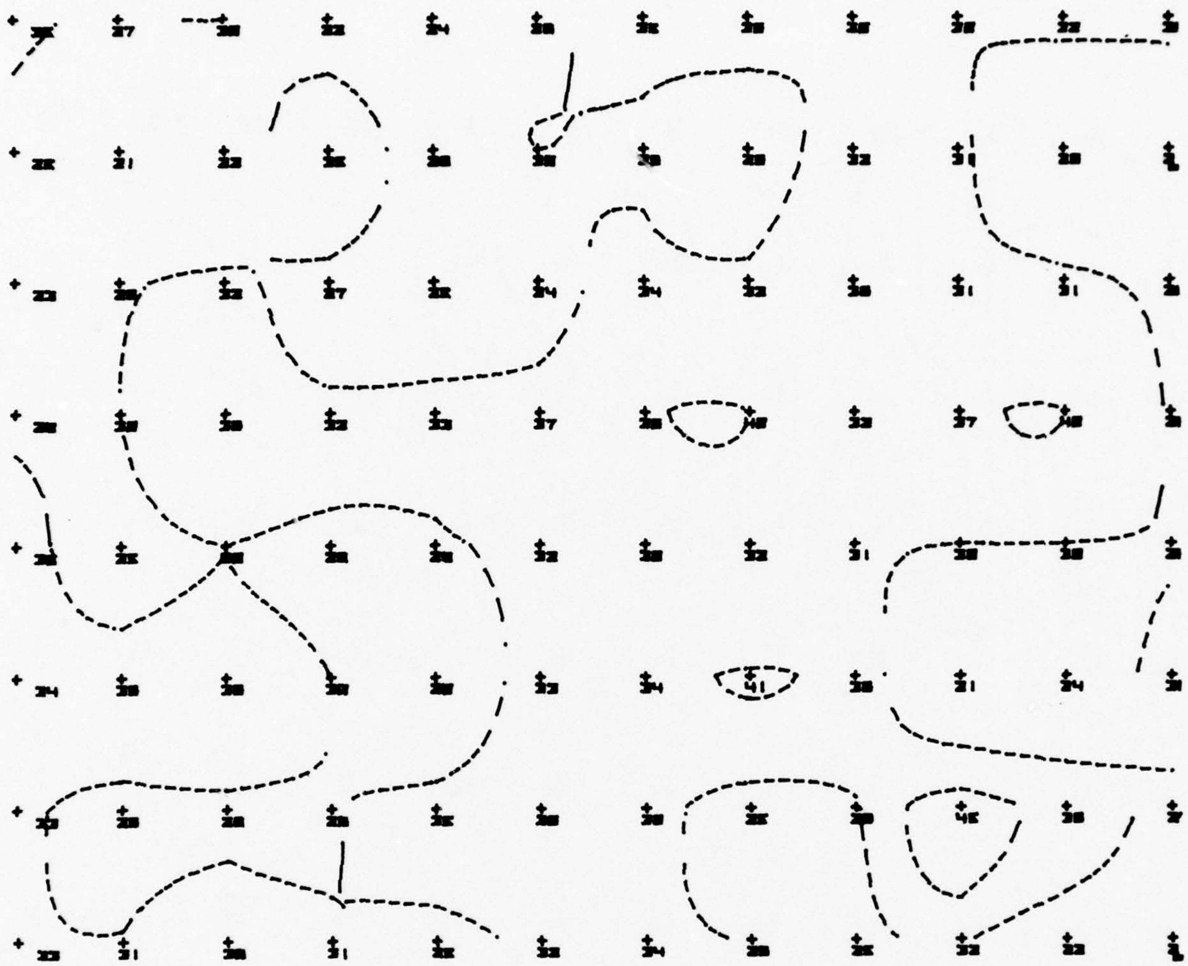


FIGURE 11d - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 6 OF INTACT STANDARD TORSION TUBE.

STD TUBE SEC #6

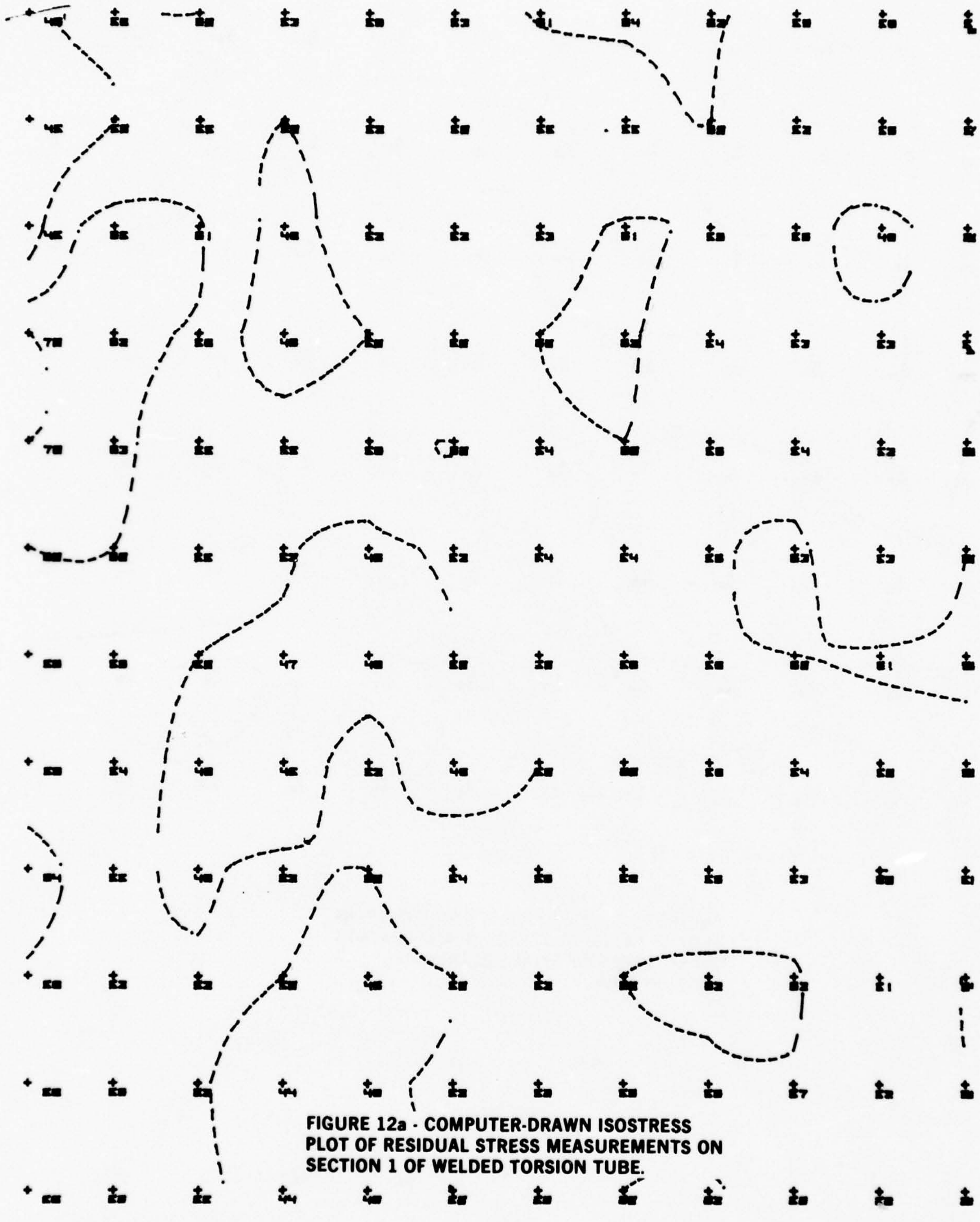


FIGURE 12a - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 1 OF WELDED TORSION TUBE.

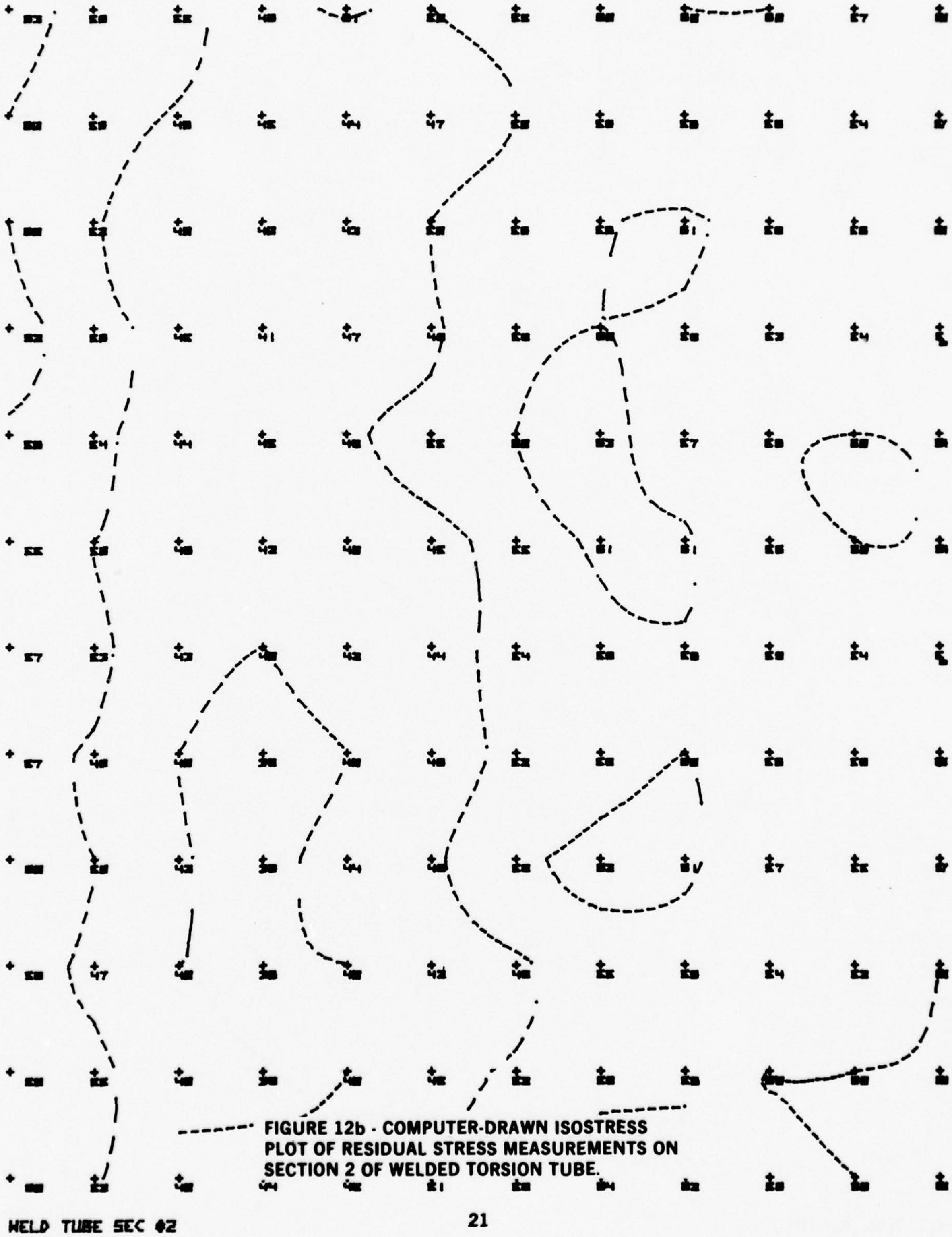


FIGURE 12b - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 2 OF WELDED TORSION TUBE.

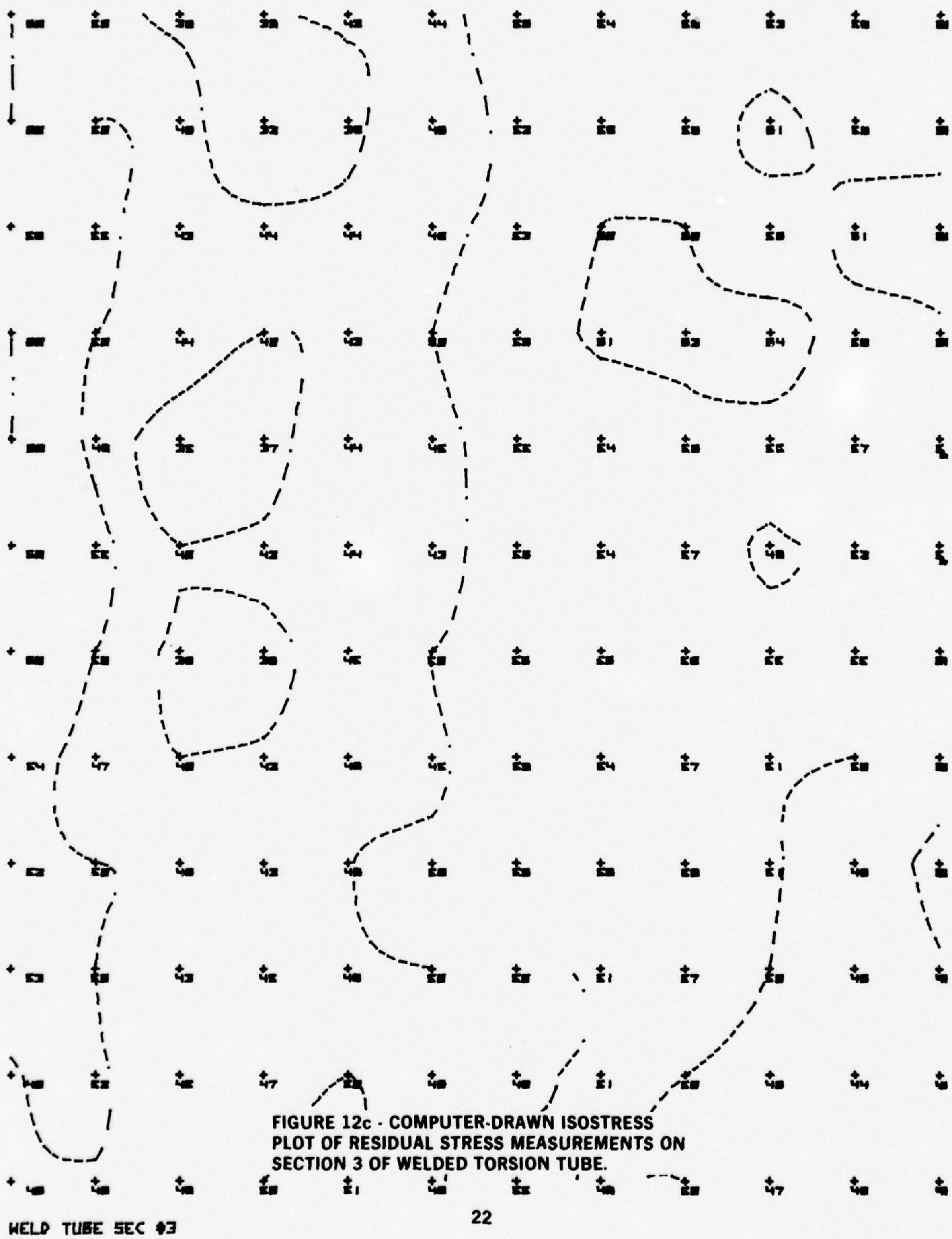


FIGURE 12c - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 3 OF WELDED TORSION TUBE.

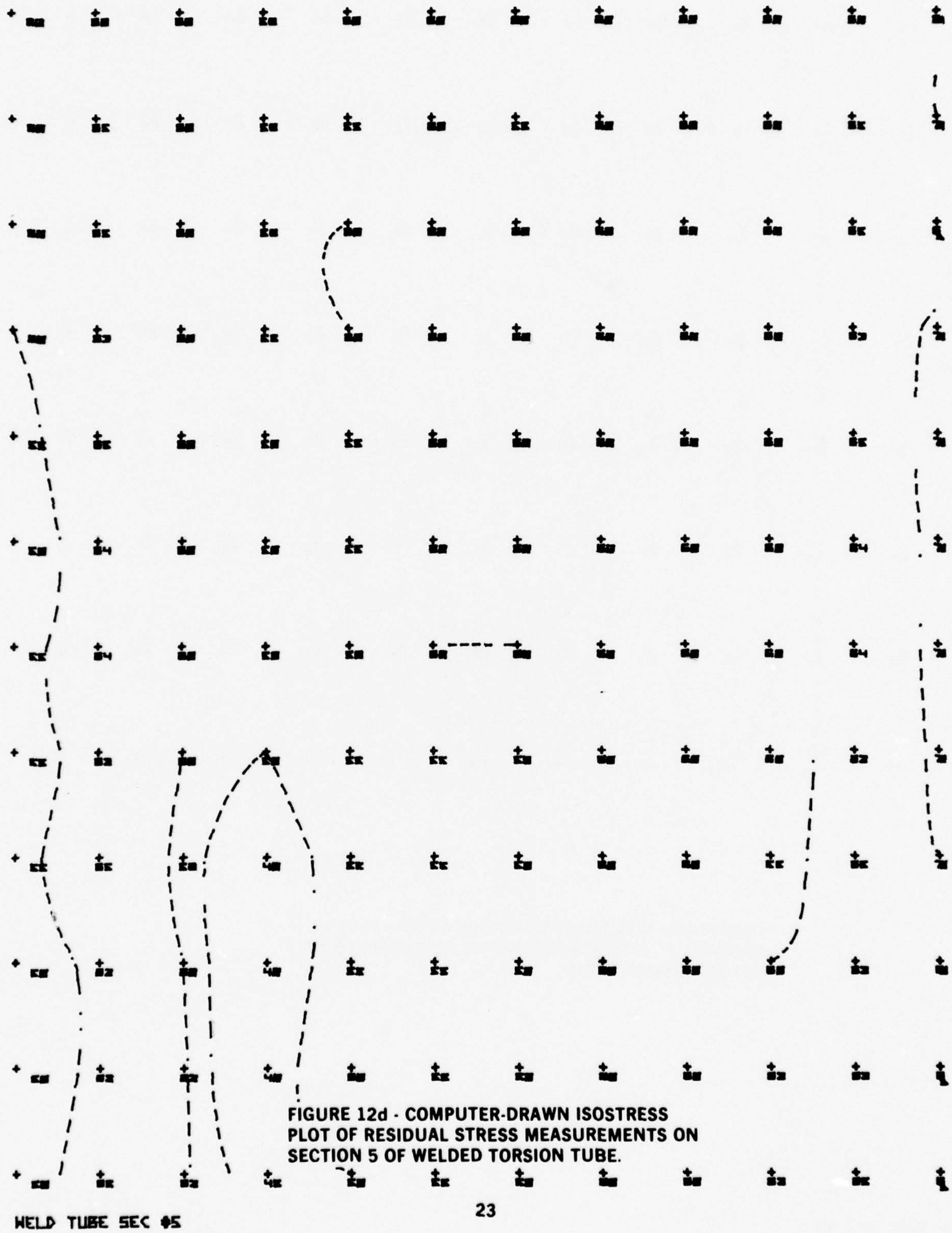


FIGURE 12d - COMPUTER-DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 5 OF WELDED TORSION TUBE.

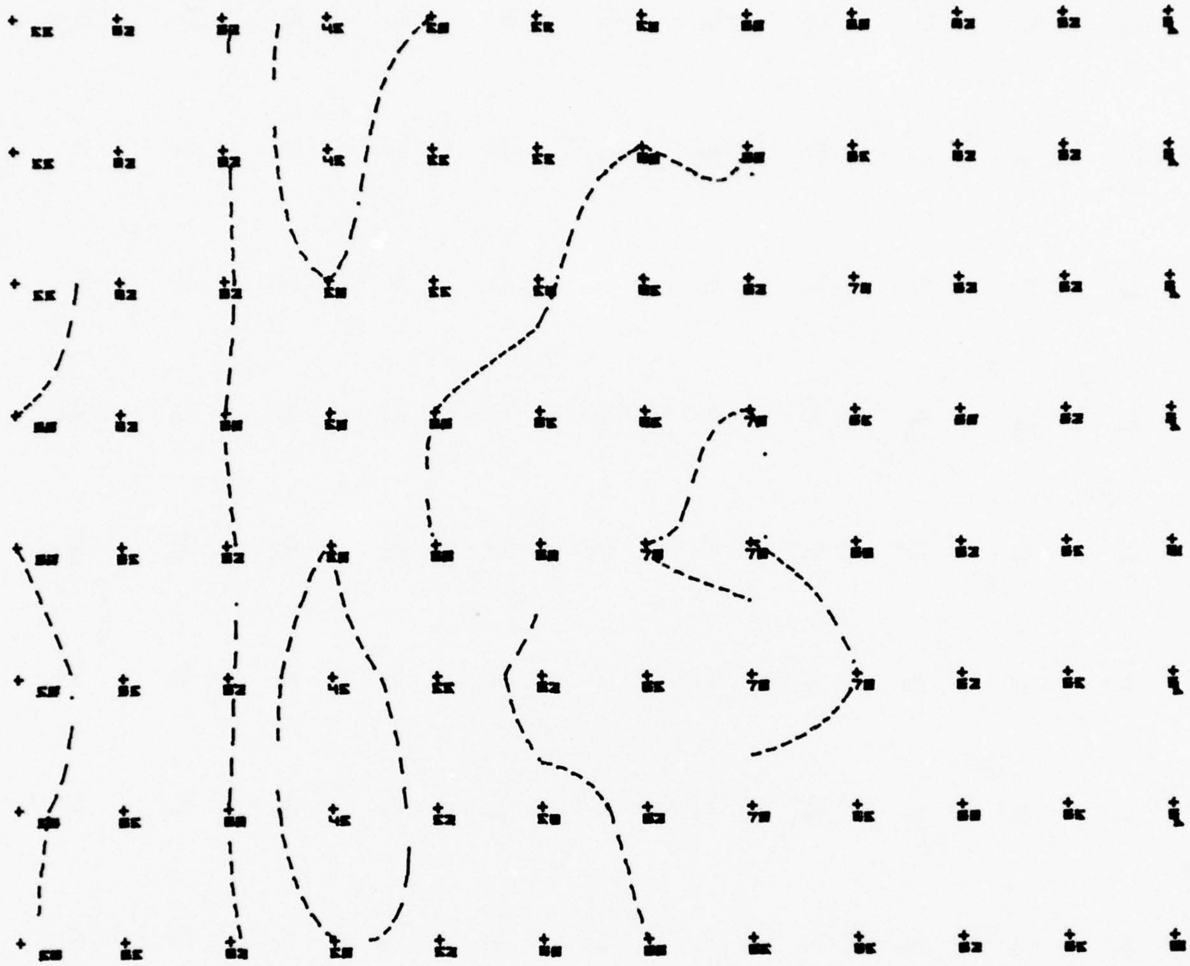


FIGURE 12e - COMPUTER DRAWN ISOSTRESS PLOT OF RESIDUAL STRESS MEASUREMENTS ON SECTION 6 OF WELDED TORSION TUBE.

WELD TUBE SEC #6

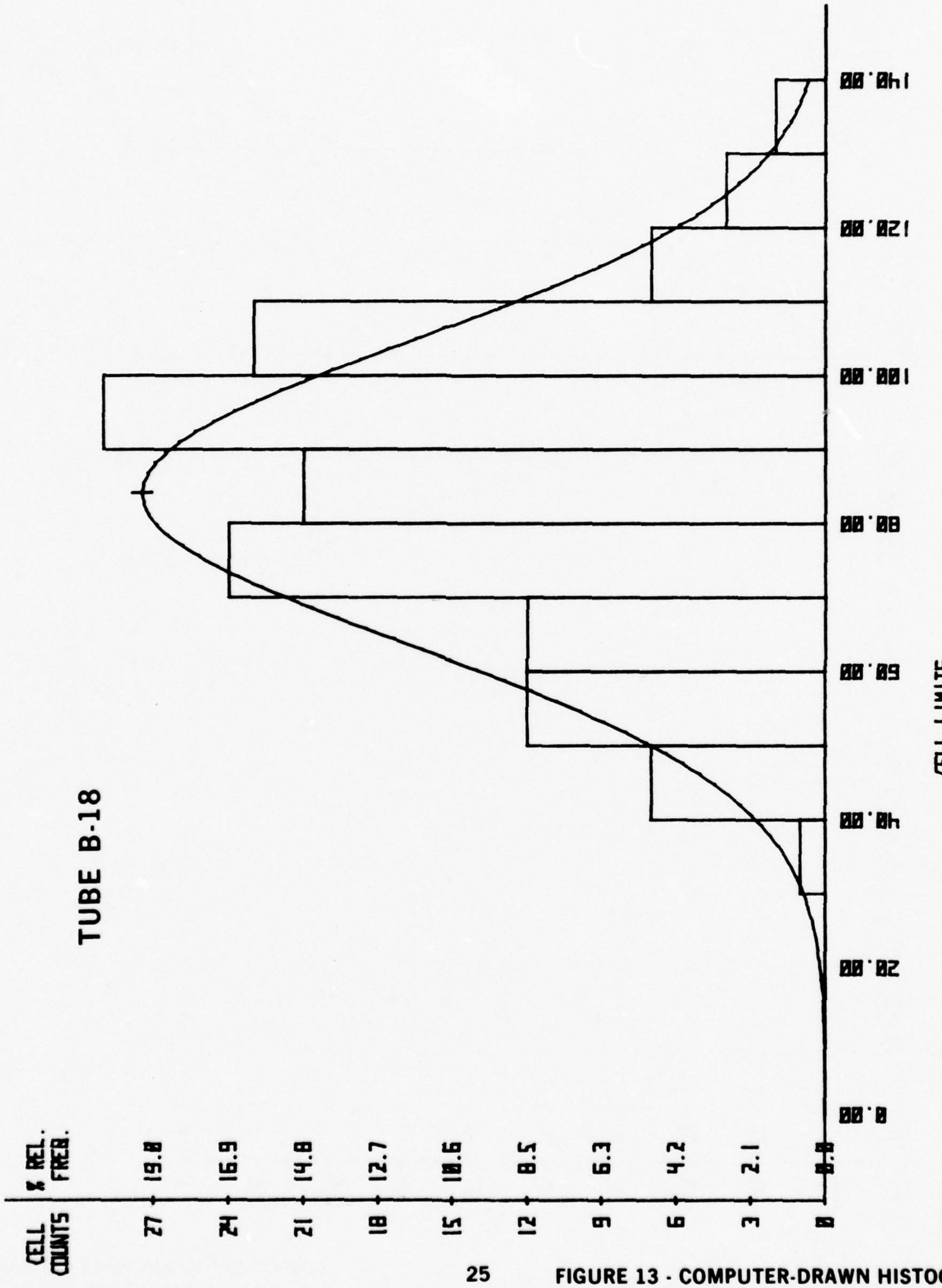


FIGURE 13 - COMPUTER-DRAWN HISTOGRAM OF DATA FROM BROKEN TORSION TUBE B-18.

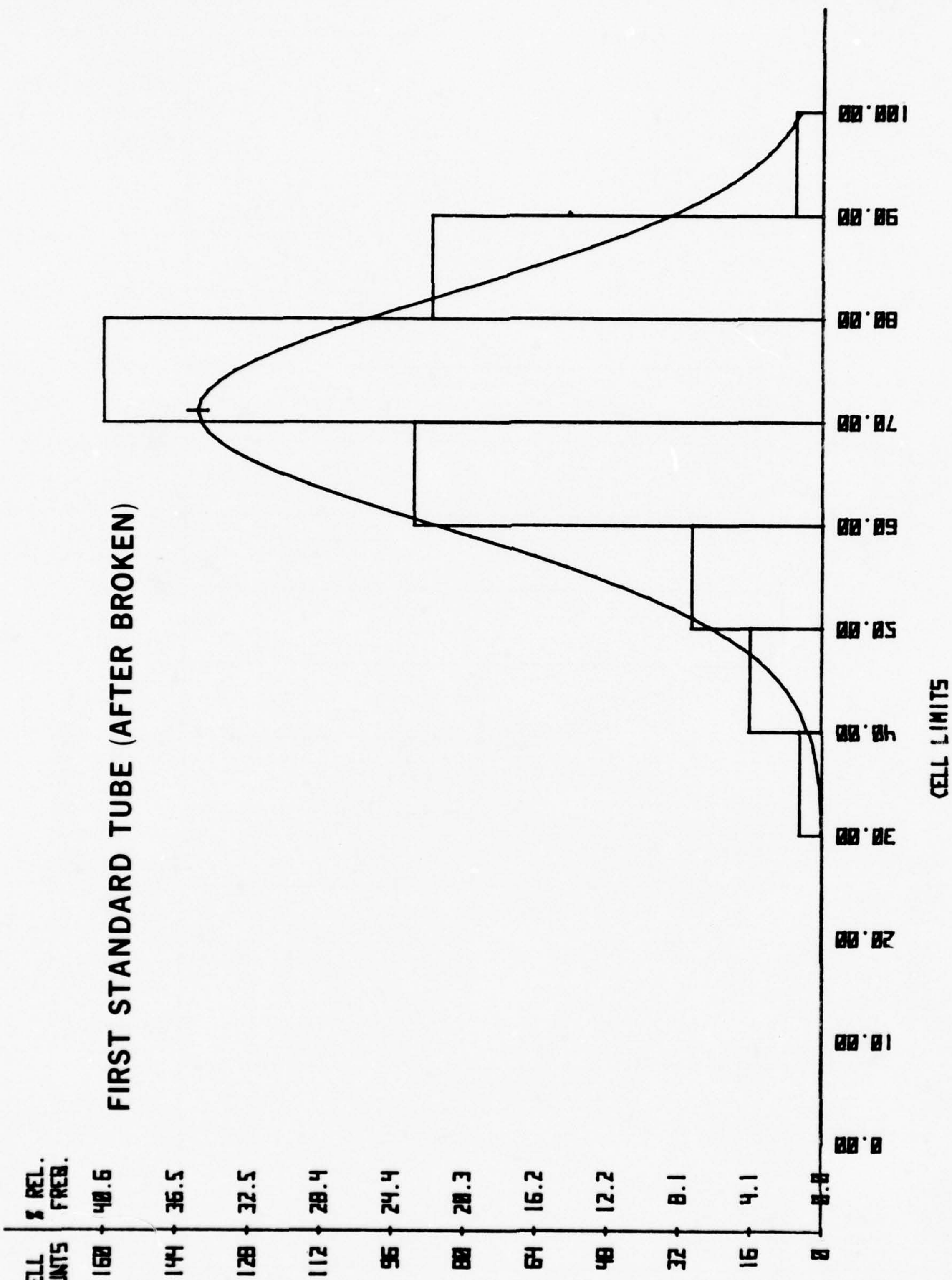


FIGURE 14 - COMPUTER-DRAWN HISTOGRAM OF DATA FROM INTACT STANDARD TORSION TUBE.

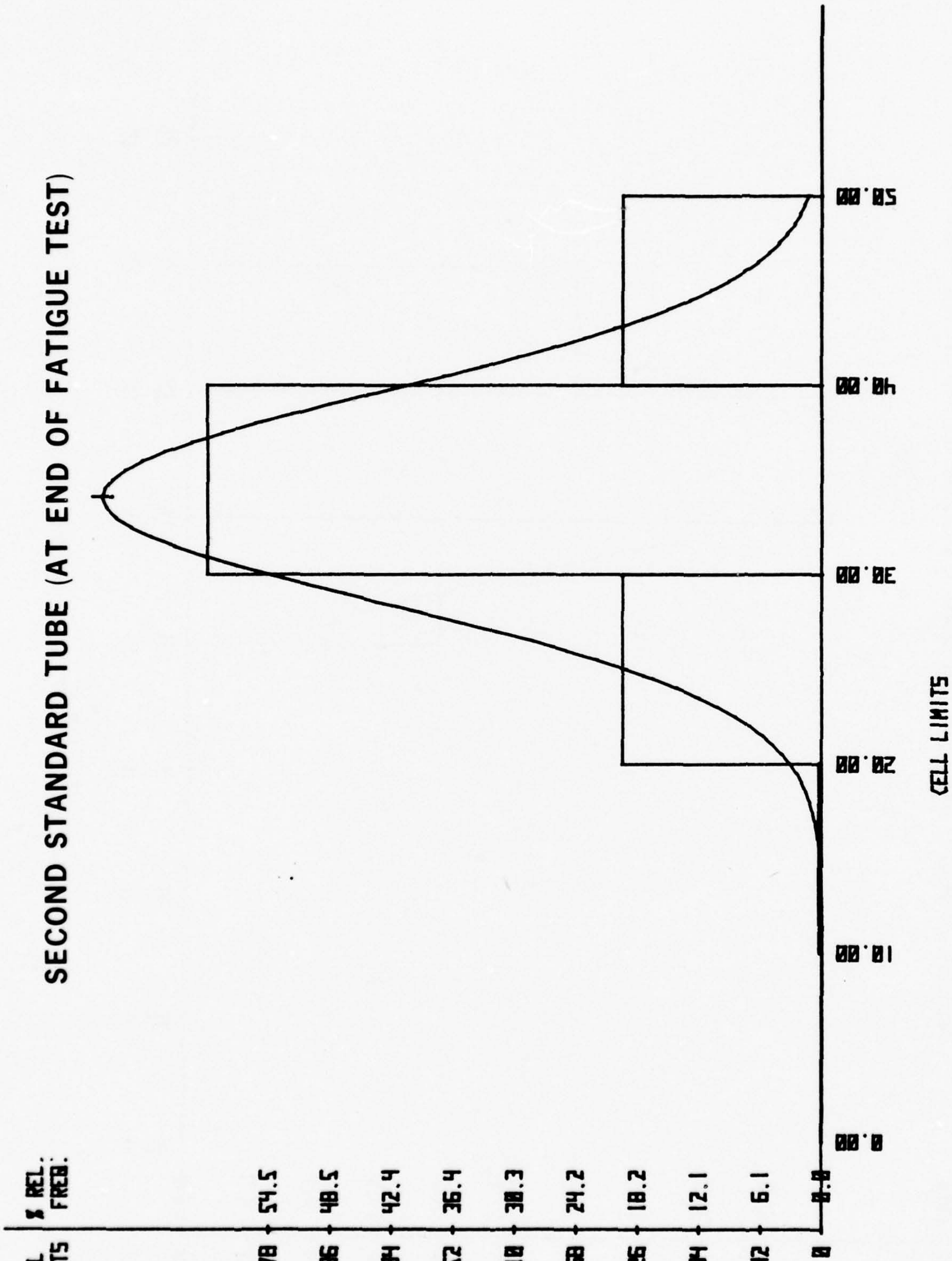


FIGURE 15 - COMPUTER-DRAWN HISTOGRAM OF DATA FROM INTACT STANDARD TORSION TUBE.

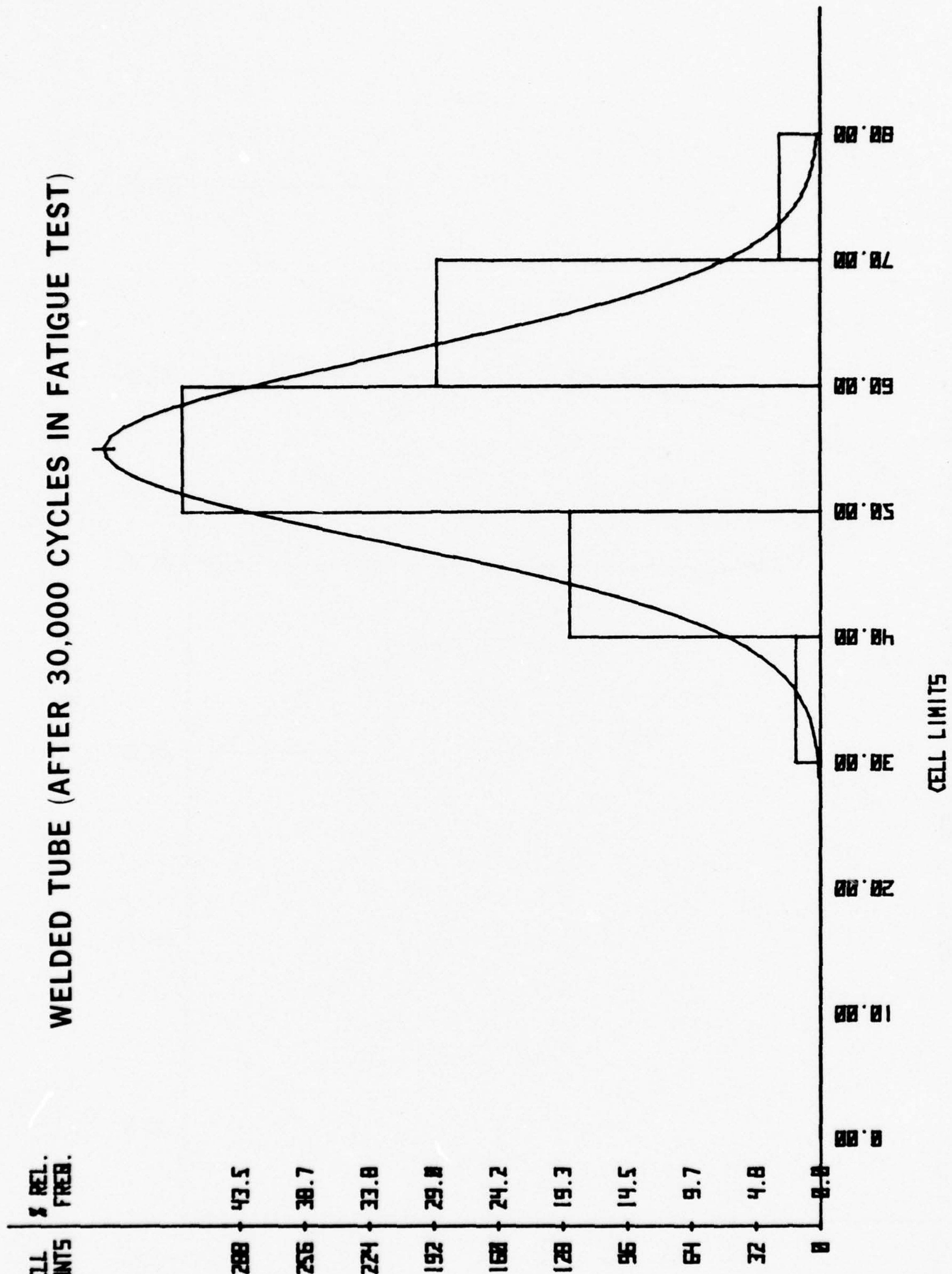


FIGURE 16 - COMPUTER DRAWN HISTOGRAM OF DATA FROM INTACT STANDARD TORSION TUBE.

Figure 17 - Torsion tubes with their associated isostress patterns attached. The two tubes on the left survived fatigue test and display much more uniform isostress patterns than the two tubes on the left, both of which failed fatigue test.

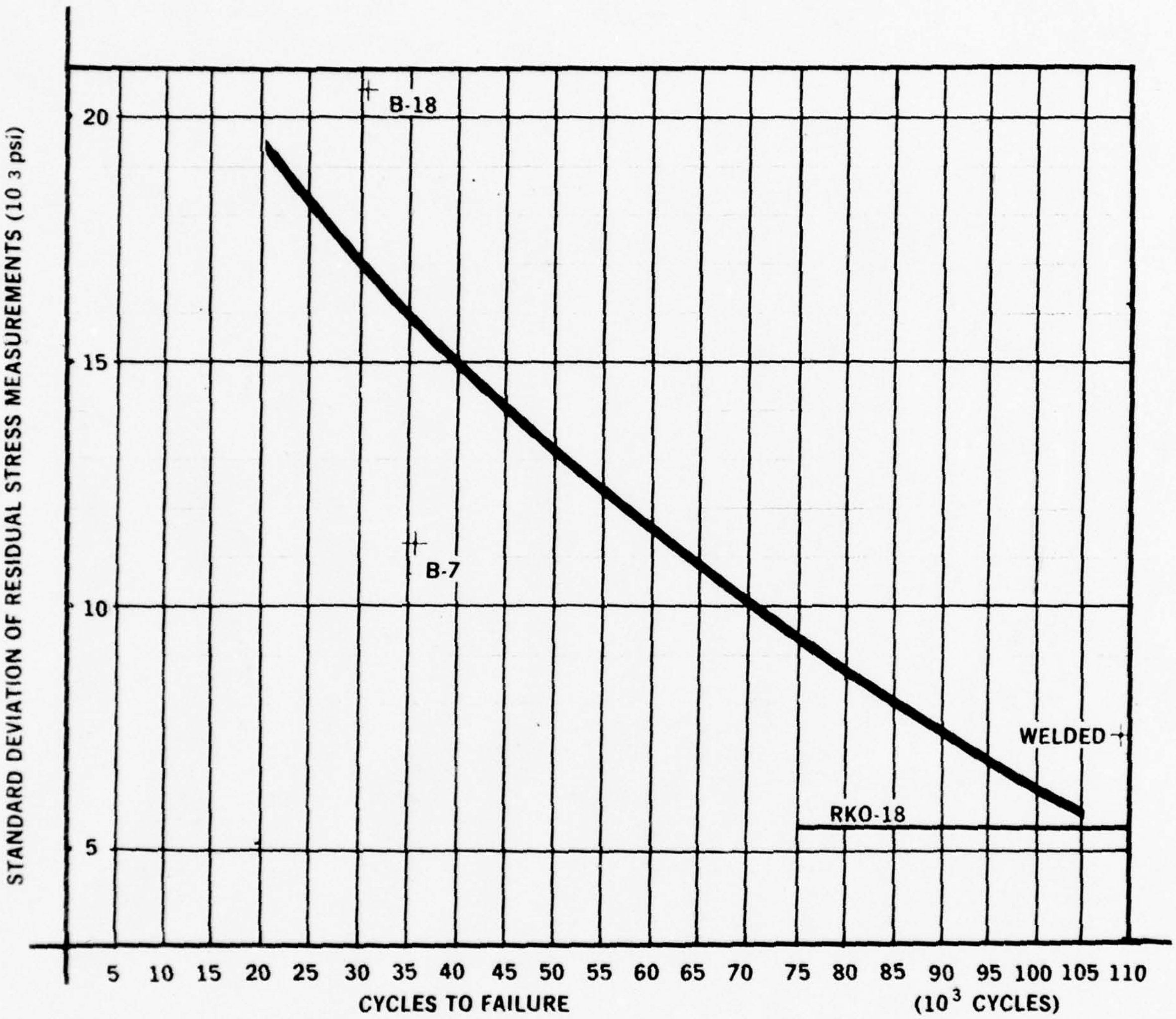


FIGURE 18 PLOT OF STANDARD DEVIATION OF MEASURED RESIDUAL STRESS VS. CYCLES TO FAILURE IN FATIGUE TEST FOR THE FOUR TORSION TUBES TESTED.

TABLE I

TORSION TUBE NUMBER	CYCLES TO FAILURE	NUMBER OF RESIDUAL STRESS READINGS	RESIDUAL STRESS MEAN	RESIDUAL STRESS STD. DEVIATION	SKEWNESS	KURTOSIS
B-18	30,593	142	-84×10^3 psi	20.6×10^3 psi	-0.15×10^3 psi	2.54×10^3 psi
B-7	35,582	394	-71×10^3	11.3×10^3	-0.82×10^3	3.80×10^3
WELDED	$>$ 109,000	662	-55×10^3	7.4×10^3	-0.25×10^3	2.68×10^3
RKO-18	(Didn't fail after 75,000 cycles)	693	-34×10^3	5.6×10^3	-0.16×10^3	2.65×10^3

APPENDIX

COMPUTER PROGRAM

```
10 DIM N[9],XS[50,2],YS[50,2]
20 DIM DS[51,3],L[9],M[9,9],GS[40],KI[3,2],II[3],JI[3],HI[20]
30 DISP "NO. OF Y ROWS, NO. OF X COLS.";
40 INPUT K5,J5
50 DISP "LOAD INCREMENT";
52 INPUT Q
54 DISP "SENSITIVITY";
56 INPUT S
58 S=S*(S >= 0.25)+0.25*(S<0.25)
70 ENTER (4,80)(FORJ=1TO20,H[J])
80 FORMAT 20B
90 FOR X=1 TO 40
100 G[X]=COSATNX
110 NEXT X
120 D1=0.2*S
140 SCALE K5+0.5,0,0.9,J5+0.1
150 PLOT 0.5,1,0
160 FOR J=1 TO 20
170 IF H[J]=10 OR H[J]=13 THEN 210
180 LABEL (190,1,1.5,PI/2,0.72)H[J];
190 FORMAT B
200 NEXT J
210 LABEL (1950,0.6,1,0.5*PI,0.72)
250 K2=K5-2
260 FOR K=2 TO 1 STEP -1
270 GOSUB 1870
280 NEXT K
300 FOR K2=K5-3 TO 0 STEP -1
310 FOR K=2 TO 1 STEP -1
320 FOR J=1 TO J[K]+1
330 D[J,K+1]=D[J,K]
340 NEXT J
342 I[K+1]=I[K]
344 J[K+1]=J[K]
346 K[K+1,1]=K[K,1]
348 K[K+1,2]=K[K,2]
360 NEXT K
370 K=1
380 GOSUB 1870
385 GOSUB 2030
390 J1=J[1]*(J[1]>J[2])+J[2]*(J[1] <= J[2])
400 FOR J2=I[1]-1 TO J1-3
410 Y1=K2+1
420 Y2=K2+2+(K2=K5-3)
430 X1=J2+1
435 IF X1 >= K[1,1] AND X1<K[1,2] THEN 470
440 B1=J2+2
450 GOSUB 1250
460 GOSUB 530
470 NEXT J2
500 NEXT K2
510 PLOT 0.1,1,0
515 DISP "COMMENTS";
517 LETTER
```

```
520 END
530 M1=1000
540 M2=-1000
550 FOR K=1 TO Y2-Y1+1
554 J6=X1*(B1 <= J[K])+(J[K]-B1+X1)*(B1>J[K])+(I[K]-1>J6)*(I[K]-1-J6)
560 FOR J=0 TO B1-X1
562 J3=J+J6
580 Y=D[J3,K]
585 IF Y=8888 THEN 630
590 IF Y>M1 THEN 610
600 M1=Y
610 IF Y<M2 THEN 630
620 M2=Y
630 NEXT J
640 NEXT K
650 M1=(INT(M1/Q)+1)*Q
660 M2=INT(M2/Q)*Q
670 FOR Z=M1 TO M2 STEP Q
680 X3=X1
690 E2=0
700 D2=0.39
710 FOR X=X3 TO B1+D2 STEP D2
720 GOSUB 1510
730 IF E1=0 THEN 780
740 NEXT X
750 IF D2<0.025*S THEN 1190
760 D2=0.5*D2
770 GOTO 710
780 X3=X-D2*(X>X1)
790 D2=0.5*D2
800 IF D2>0.025*D1 THEN 710
810 D2=0.025*D1
820 E2=0
830 X=X3
840 N2=N3=1
850 GOSUB 1510
860 E3=(E1#0)*((E2#0)+1)
870 GOTO E3 OF 900,920
880 GOSUB 1710
890 D2=G[I1]*D1
900 X=X+D2
910 IF X<B1 THEN 850
920 N4=N2-1
930 X3=X
940 I8=-2
950 I9=-(Z>0)
960 X6=0.02*(Z=0)
970 E2=0
980 FOR J=1 TO 2
990 IF N4<2 THEN 1120
1000 X4=X[1,J]
1010 FOR X5=0 TO X6 STEP X6+(X6=0)
1020 FOR N=1 TO N4
```

```
1030 IF X[N,J]-X4<D1 THEN 1050
1040 PEN
1050 I8=I8+I9
1060 PLOT Y[N,J]+X5,X[N,J]+X5,I8
1070 X4=X[N,J]
1080 NEXT N
1090 PLOT Y[N-1,J]+X5,X[N-1,J]+X5
1100 PEN
1110 NEXT X5
1120 PEN
1130 N4=N3-1
1140 I8=-2
1150 NEXT J
1160 IF X >= B1 THEN 1190
1170 D2=0.1
1180 GOTO 840
1190 NEXT Z
1200 IF B1#J1-1 THEN 1240
1210 X1=B1
1220 B1=B1+1
1230 GOTO 530
1240 RETURN
1250 I=0
1260 FOR K3=1 TO 3
1270 K=K3+K2
1280 J6=J2
1282 IF J2 >= I[K3]-1 THEN 1290
1284 J6=I[K3]-1
1290 IF J2<J[K3]-3 THEN 1310
1300 J6=J[K3]-3
1310 FOR J=1 TO 3
1320 J3=J+J6
1330 I=I+1
1340 L[I]=D[J3,K3]
1350 M[I,1]=1
1360 M[I,2]=J3
1370 J4=J3*J3
1380 M[I,3]=J4
1390 M[I,4]=K
1400 K4=K*K
1410 M[I,5]=K4
1420 M[I,6]=J3*K
1430 M[I,7]=J4*K
1440 M[I,8]=J3*K4
1450 M[I,9]=J4*K4
1460 NEXT J
1470 NEXT K3
1480 MAT M=INV(M)
1490 MAT N=M*L
1500 RETURN
1510 E1=0
```

```
1530 A=(N[9]*X+N[8])*X+N[5]
1540 IF A=0 THEN 1590
1550 B=(N[7]*X+N[6])*X+N[4]
1560 C=(N[3]*X+N[2])*X+N[1]-Z
1570 R2=B*B-4*C*A
1580 IF R2>0 THEN 1610
1590 E1=1
1600 RETURN
1610 R1=SQRR2*SGNA
1620 A=0.5/A
1630 Y3=(-B+R1)*A
1640 Y4=(-B-R1)*A
1650 E4=Y3>Y1 AND Y3<Y2
1660 E5=Y4>Y1 AND Y4<Y2
1670 E6=E4+2*E5
1680 IF E6=0 THEN 1590
1690 E2=1+E2
1700 RETURN
1710 Y5=20
1720 GOTO E6 OF 1730,1780,1750
1730 IF N2<2 THEN 1750
1740 Y5=ABS(Y3-Y[N2-1,1])
1750 Y[N2,1]=Y3
1760 X[N2,1]=X
1770 N2=1+N2
1780 IF E5=0 THEN 1840
1790 IF N3<2 THEN 1810
1800 Y5=ABS(Y4-Y[N3-1,2])
1810 Y[N3,2]=Y4
1820 X[N3,2]=X
1830 N3=N3+1
1840 I1=Y5/D2
1850 I1=I1+(I1<1)-(I1-40)*(I1>40)
1860 RETURN
1870 ENTER (4,*)(FORJ=1TOJ5+1,D[J,K])
1872 J1=J2=0
1874 K[K,1]=K[K,2]=J5
1880 FOR J=1 TO J5+1
1882 GOTO J1 OF 1890
1884 IF D[J,K]=8888 THEN 1960
1886 I[K]=J
1888 J1=1
1890 IF D[J,K]=9999 THEN 1970
1892 IF D[J,K]#7777 THEN 1908
1894 D[J,K]=RND1
1896 IF J2#0 THEN 1900
1898 K[K,1]=J
1899 J2=1
1900 IF D[J+1,K]=7777 THEN 1906
1902 K[K,2]=J
1906 GOTO 1960
1908 PLOT K+K2,J,0
1910 CPLOT -0.25,-0.25
1920 LABEL (*)"+"
1930 CPLOT -2,0
1940 LABEL (1950)D[J,K]
1950 FORMAT F4.0
```

```
1960 NEXT J
1970 J[K]=J-1
2020 RETURN
2030 J=(K[1,1]=J5)+2*(K[2,1]=J5)
2040 GOTO J+1 OF 2070,2140,2050,2170
2050 PLOT K2+1,K[1,1]
2060 PLOT K2+1,K[1,2]
2062 PEN
2065 RETURN
2070 PLOT K2+1,K[1,2]
2080 PLOT K2+2,K[2,2]
2090 PEN
2100 PLOT K2+2,K[2,1]
2110 PLOT K2+1,K[1,1]
2120 PEN
2130 RETURN
2140 PLOT K2+2,K[2,1]
2150 PLOT K2+2,K[2,2]
2160 PEN
2170 RETURN
```

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An automatic stress analyzer has been used by the U.S. Army Tank-Automotive Research and Development Command (TARADCOM), for rapid measurement of residual stresses in track pins and torsion tubes. With this equipment measurements can be made from ten to one-hundred times faster than with conventional equipment. The equipment is a recent development and few are in existance. A unique feature of the unit at TARADCOM is that it has been interfaced with a computer for purposes of drawing isostress plots.

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Block 20 continued.

Work on used track pins showed no detrimental residual stress levels on the surface of the track pins. Measurements taken on sectioned surfaces of track pins revealed areas of tensile residual stress surrounded by compressive residual stresses, with steep stress gradients in between. These areas are in the region between the core and the induction hardened layer; cracking was observed here in laboratory tested track pins.

Vast differences are exhibited in both the isostress plots and the standard deviation of the measurements taken on torsion tubes where failure initiation occurred on the bodies of the tubes as opposed to instances where failure initiation did not occur in the body of the tube or where failure did not occur at all. These differences may be due to differences in the uniformity of the shot peening operation. Regions of lower compressive residual stress and associated steep stress gradients may act as stress risers and cause premature failure.